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Multi-Layer Soft Frequency Reuse Scheme for 5G Heterogeneous Cellular Networks

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***Abstract*—Heterogeneous network (HetNet) is a promising cell deployment technique where low power access points are deployed overlaid on a macrocell system. It attains high throughput by intelligently reusing spectrum, and brings a trade-off between energy- and spectral-efficiency. An efficient resource allocation strategy is required to significantly improve its throughput in a bid to meet the fifth-generation (5G) high data rate requirements. In this correspondence, a new resource allocation scheme for HetNet, called multi-level soft frequency reuse for HetNet (ML-SFR HetNet), is proposed which increases the throughput several fold. In ML-SFR HetNet, mutually exclusive spectrum is allocated for macro and small cell users and well as for cell edge users among the various cells in the reuse system. We derived spectrum and power allocation expression for a generalized HetNet scenario. In addition, analytical expressions for the throughput and area spectral efficiency (ASE) are also developed. The simulations results demonstrates the efficiency of the proposed scheme which improves the throughput by around 3.5 times and outage probability reduces nearly 5 times compared to traditional SFR system.**

Keywords—Heterogeneous Cellular Networks (HCN), Soft Frequency Reuse (SFR), ML-SFR, Area Spectral Efficiency (ASE), 5G.

I. Introduction

Wireless communication networks are experiencing an unprecedented growth in the data rate requirement in recent times. Increasing the network area spectral efficiency (ASE) [1] in order to serve such demanding data rates is an important research challenge. A major impediment to improving the ASE, especially at cell edges, is the inter-cell interference (ICI) [2]. Fractional Frequency Reuse (FFR) [3], and its variants such as Soft frequency reuse (SFR) are widely researched techniques proposed to manage the ICI [4] [5].

In SFR, each cell is divided into a center-zone and a cell-edge-zone. For the cell centre zone of each cell, the full spectrum is made available for the users. However, in the cell edge zone, only a small chunk of the spectrum is made available in such as way that the spectrum allocated to the cell edge zones of the neighbouring cells are mutually exclusive. This ensures that the users in the cell edge-zone will experience lower ICI compared to the conventional frequency reuse scheme. This limited spectrum at the cell edge may result in limited capacity for the cell edge users. However, since the spectrum are mutually exclusive, the high power carriers are allocated to the users in this zone and thereby improve the overall ASE of the system [6]. In [7] it has been shown that SFR outperforms FFR when the cells are loaded partially and the opposite is true in full load condition.

Recently, a multi-level SFR (ML-SFR) has been proposed in [8], where each cell is divided into an even number (more than two) of zones with the transmit power level divided accordingly. This approach achieves a limited spectral efficiency (SE) improvement due to a limited reduction of ICI. To further improve the SE, ML-SFR for sectored macrocell is proposed in [9]. However, such an increase in the SE is obtained at the expense of reduced spectrum reuse, resulting in a limited gain in terms of the system throughput in single-tier network.

In the classical single-tier network, the spectrum is reused within a cell by incorporating different types of cell types with different power levels. Such networks are called heterogeneous networks (HetNets). In HetNets, a number of low power small cell base stations, called home evolved node Bs (HeNBs), cooperatively share the available spectrum with a overlaid macro cell served by a higher power macro evolved node B (MeNB). HetNets allows offloading a significant part of the traffic from macro cells to small ones. The small cells are usually densely deployed, thus changing the overall interference pattern in the network and making interference management more difficult. The cell throughput of a HetNet depends on the degree of spectrum reuse and effective interference management.

To improve the reuse degree, SFR has been adopted in HetNet, thereby making SFR HetNet, in [10]. However, the improvement is limited due to the limited reuse of spectrum. Another reason of limited improvement is due to the fact that, in most cases, SFR is designed solely for reducing ICI without considering the potential benefit in the HetNet environment. Given the nature of mutually exclusive sharing of the spectrum in HetNet, it is intuitive that increasing the number of zones will allow more spectrum to be available for small cells in various zones. Thus, in order to substantially improve the cell throughput a ML-SFR HetNet is proposed in this correspondence. The signal-to-interference and noise ratio (SINR) and area spectral efficiency (ASE) of the proposed scheme are derived and compared against conventional SFR. ML-SFR HetNet is found to achieve better cell throughput and ASE over the conventional SFR-HetNet scheme. Moreover, the

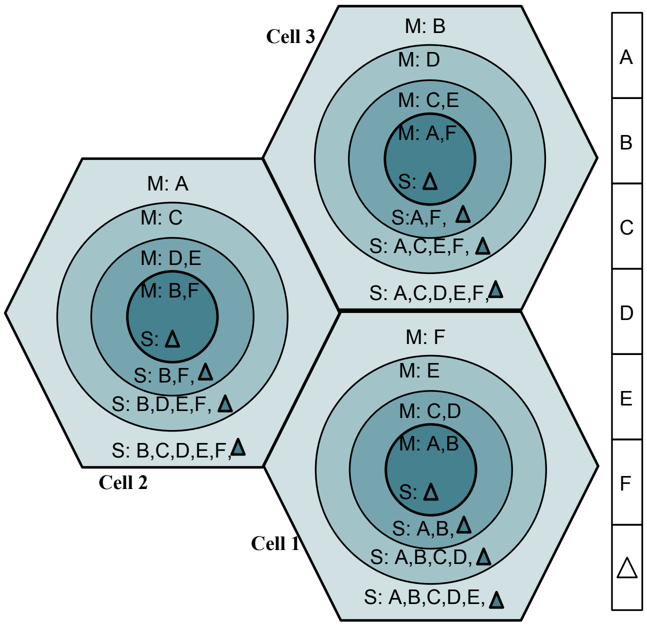

Fig. 1. Spectrum allocation for $N = 4$ and $\kappa = 3$.

outage probability of the proposed scheme is also found to be better than that of the baseline scheme. It should be noted that the SFR schemes are generally designed for the downlink which is also followed in this work.

Rest of the paper is organised as follows: Section II discusses the ML-SFR in HetNet scenario while Section III is focused on performance indicators formulation and analysis. Detailed performance results are provided in Section IV and finally the paper concludes in Section V.

II. Multi-level SFR Heterogeneous Network

In conventional SFR HetNet, each cell is divided into a cell centre-zone and a cell-edge-zone similar to the SFR for homogeneous macrocell networks. For cluster size of κ, the available bandwidth is divided into κ sub-bands. For macro user equipment (MUE), the spectrum allocated to the center-zone is twice the spectrum allocated to the cell-edge-zone. The allocated spectrum for small-cell user equipment (SUE) in a certain zone is mutually exclusive to the spectrum allocated to the MUE in that zone. However, this condition alone is not sufficient for eliminating cross-tier (between macro and small-cell user) interference in a certain place as the spectrum used by MUEs in the cell-edge-zone will create stronger interference to any user operating on the same frequency in the cell centre region and therefore cannot be used in the cell-center. To overcome this problem, the spectrum used in the cell-edge-zone for MUEs is only used in the center-zone if it is not being used in the cell-edge-zone. This strategy, however, cannot ensure full-time availability of the spectrum for SUEs in the center-zone.

In ML-SFR HetNet, we propose to employ multiple conventional SFR schemes in each cell. For SFR-N (where $\frac{N}{2}$ conventional SFR schemes are employed), we divide the cell into N circular zones, and allocate spectrum and power to each zone so as to keep interference minimum. For SFR-N, the available bandwidth is divided into $\beta = N + \frac{N}{2} + 1$ sub-bands. If B_w is the available bandwidth, each sub-band spectrum is $\xi = \frac{B_w - \Delta}{\beta - 1}$, where Δ is the spectrum reserved for small cells in each level to ensure the full availability of spectrum in the center-zone. To describe the spectrum allocation, let us consider that $\kappa = 3$. We will first allocate spectrum for macro cells. If A and B are the spectrum used in the i^{th} level, where $i \leq \frac{N}{2}$, in the cell 1, these are allocated to the $(N+1-i)^{th}$ and i^{th} levels of the cell 2, respectively, and i^{th} and $(N+1-i)^{th}$ levels in the cell 3, respectively. However, if the spectrum C is allocated to the i^{th} level, where $i > \frac{N}{2}$, of cell 1, it will be allocated to the $(N+1-i)^{th}$ level in rest of the cells. On the other hand, the spectrum allocated for small cells in the i^{th} level in a cell is given by:

$$\delta_i^S = \sum_{j=1}^{i-1} \delta_j^M + \Delta \tag{1}$$

where δ_j^M is the spectrum allocated to the j^{th} level for MeNBs. Figure 1 shows the spectrum allocation for $\kappa = 3$ and $N = 4$. The first and fourth levels form a SFR, and the second and third form another SFR, called the second SFR. It shows that the spectrum for small cells increases with the increase of the levels of SFR.

While the narrowest spectrum will be available for small cells in the first level, the widest spectrum will be available in the cell-edge-zone. The increased spectrum results in more channels, which culminates in more cell throughput. It is pertinent to mention here that the spectrum for MeNB will remain same like homogeneous macro cellular network.

The power allocation in ML-SFR HetNet is less complex than the spectrum allocation. While the HeNBs of all levels use a particular low power P_s, the MeNBs use different power depending on the SFR levels it is serving in. If P is the power of the cell-edge-zone serving MeNB, the power allocated to the i^{th} level is given by [9]:

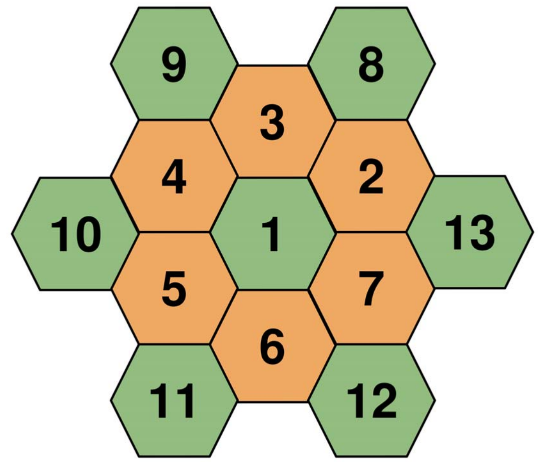

Fig. 2. 13-Cells cellular network system model.

$$P_i = \begin{cases} P & \text{for } \ i = N \\ \alpha_{i-\frac{N}{2}+1} P & \text{for } \ \frac{N}{2} < i < N \\ \gamma_i P_{N+1-i} & \text{for } \ 1 \le i \le \frac{N}{2} \end{cases} \tag{2}$$

where α_i is the ratio of the outer-zone power of the i^{th} SFR to the power of the outer-most-zone of the cell. For example, for SFR-4, which consists of two SFRs, α_2 is the ratio of the outer-zone power, P_3 of the second SFR to the outer-most-zone power, P_4. The parameter γ_i, on the other hand, represents the ratio of the outer-zone power and inner-zone power of the i^{th} SFR.

III. System Performance Modelling

In this section, we formulate the key performance indicators such as cell throughput, outage probability and area spectral efficiency (ASE) for ML-SFR HetNet system. We assume that HeNBs are randomly deployed in a cell. There is a transmitter for each level; for example, i^{th} transmitter transmits to the i^{th} level.

A. Signal-to-interference-plus-noise ratio (SINR)

The SINR of MUE j with sub-channel k located in the i^{th} level is given by:

$$SINR_{j,i}^{k,M} = \frac{P_i^{k,0} G_{j,i}^{k,0}}{N_o \Delta_f + I_{j,i}^{k,M} + I_{j,i}^{k,S}} \tag{3}$$

where $P_i^{k,0}$ is the transmit power from the desired transmitter on the k^{th} sub-channel allocated to the i^{th} level, $G_{j,i}^{k,0}$ is the channel gain associated with the k^{th} subchannel employed in the i^{th} level for the j^{th} MUE, and $G_{j,i}^{k,0} = 10^{-P_L/10}$ where P_L is the outdoor or indoor path loss, N_o and Δ_f are noise spectral density and sub-carrier spacing, respectively, $I_{j,i}^{k,M}$ and $I_{j,i}^{k,S}$ are the interference experienced by the j^{th} MUE from the MeNBs of other cells and HeNBs located within the cell, respectively. A MUE j in the level i does not experience equal interference from all cells in the first-tier; rather, any MUE j in the level i with $1 < i \le \frac{N}{2}$ experiences interference from the i^{th} MeNB of the half of the cells in the tier-1 and from the $(N+1-i)^{th}$ MeNBs of the rest of the cells of the tier-1. However, for $\frac{N}{2} < i \le N$, a MUE of level i experiences interference from the i^{th} MeNBs of all cells of tier-1. The interferences $I_{j,i}^{k,M}$ and $I_{j,i}^{k,S}$ are defined as follows:

$$I_{j,i}^{k,M} = \begin{cases} \sum\limits_{m\epsilon\Omega_1} P_i^{k,m} G_{j,i}^{k,m} + \sum\limits_{m\epsilon\Omega_2} P_{N+1-i}^{k,m} G_{j,i}^{k,m} \\ + \sum\limits_{m\epsilon\Omega_3} P_i^{k,m} G_{j,i}^{k,m} \text{for } \ 1 < i \le \frac{N}{2} \\ \\ \sum\limits_{m\epsilon\Omega_4} P_{N+1-i}^{k,m} G_{j,i}^{k,m} + \sum\limits_{m\epsilon\Omega_3} P_i^{k,m} G_{j,i}^{k,m} \\ \text{for } \ \frac{N}{2} < i \le N \end{cases} \tag{4}$$

and

$$I_{j,i}^{k,S} = \sum_{l=i+1}^{N} P_s g_{j,i}^{k,l} \tag{5}$$

where $\gamma_1 \epsilon \{2,4,6\}$, $\gamma_2 \epsilon \{3,5,7\}$, $\gamma_3 \epsilon \{8,9,10,11,12,13\}$ and $\gamma_4 \epsilon \{2,3,4,5,6,7\}$ according to Figure 2, $P_i^{k,m}$ is the transmit power of the m^{th} cell on the k^{th} sub-channel employed to the i^{th} level, and $G_{j,i}^{k,m}$ denotes the channel gain for the MUE j located in level i using k^{th} sub-channel with respect to the m^{th} interfering cell and $g_{j,i}^{k,l}$ is the channel gain of HeNB of the level l on sub-channel k for MUE j located in level i. The SINR of a SUE j located in level i using the sub-channel k is given by:

$$SINR_{j,i}^{k,S} = \frac{P_s g_{j,i}^{k,0}}{N_o \Delta_f + I_{j,i}^{k,M} + I_{j,i}^{k,S}} \tag{6}$$

where $g_{j,i}^{k,0}$ is the channel gain of the sub-carrier k assigned to the SUE j located in the i^{th} level with respect to the desired HeNB, $I_{j,i}^{k,S}$ is the interference experienced by the SUE j from all HeNBs using the same sub-channel k in level i and is given by:

$$I_{j,i}^{k,S} = \begin{cases} \sum\limits_{l=2}^{N} P_s g_{j,i}^{k,l} & \text{for } \ i = 1 \\ \\ \sum\limits_{l=K+1}^{i-1} P_s g_{j,i}^{k,l} + \sum\limits_{l=i+1}^{N} P_s g_{j,i}^{k,l} & \text{for } \ 1 < i < N \\ \\ \sum\limits_{l=K+1}^{N-1} P_s g_{j,i}^{k,l} & \text{for } \ i = N \end{cases} \tag{7}$$

where K is the level where the sub-channel k is allocated to MUE. The throughput of MUE and SUE are given by the Shannon's capacity formula:

$$C_{j,i}^{k,M} = \Delta_f . log_2(1 + SINR_{j,i}^{k,M}) \tag{8}$$

and

$$C_{j,i}^{k,S} = \Delta_f . log_2(1 + SINR_{j,i}^{k,S}) \tag{9}$$

Then the average throughput of a HetNet cell is given by

$$T = \sum_{i=1}^{N} \sum_{j=1}^{\psi_i^M} \sum_{k=1}^{\zeta_i^M} \chi_{j,i}^{k,M} C_{j,i}^{k,M} + \sum_{i=1}^{N} \sum_{j=1}^{\psi_i^S} \sum_{k=1}^{\zeta_i^S} \chi_{j,i}^{k,S} C_{j,i}^{k,S} \tag{10}$$

where ψ_i^M and ψ_i^S are the number of MUEs and SUEs in the i^{th} level, respectively, ζ_i^M and ζ_i^M denote the number of available channels for MUEs and SUEs, respectively, in the i^{th} level and $\chi_{j,i}^{k,M}$ and $\chi_{j,i}^{k,S}$ denote sub-band assignment to a user; $\chi_{j,i}^{k,M} = 1$ indicates the sub-channel k is assigned to MUE j in level i, and $\chi_{j,i}^{k,M} = 0$ indicates otherwise.

B. Outage probability

The outage probability, $P_r(Outage)$ is another important performance measure which is defined as the probability that the instantaneous SINR of the channel, k, falls below a certain threshold, Γ, at which the link quality is considered unacceptable; that is, $P_r(Outage) = P(SINR^k_{j,i}) < \Gamma$.

C. Area Spectral Efficiency (ASE)

For HetNet, the ASE is the sum of maximum achievable rates of all users per unit bandwidth per cell area supported jointly by MeNBs and HeNBs. In SFR, each channel is once used in the cell-edge-zone and $q\varepsilon\{1, 2, \ . . . \ Q - 1\}$ times in cell-center in the rest Q cells in a cluster. Hence the ASE in [bits/sec/Hz/cell] of a macro homogeneous network is given by [7]:

$$ASE_{macro} = \frac{qC_I + C_O}{\kappa}, \tag{11}$$

where C_I and C_O are spectrum efficiency over arbitrary channels in the inner and outer regions, respectively. ASE in Eq. 11 can be considered in [bits/sec/Hz/m^2] if the cell area is normalized to unity. In HetNet, each channel can be used several times depending on the requirements. Under this assumption, the ASE, denoted by ASE_i, in i^{th} level of the proposed ML-SFR HetNet can be written as:

$$ASE_i = \begin{cases} \tau . \dfrac{q\eta_i^M + \eta_{N-i+1}^M + \upsilon\left(q \sum\limits_{j=i+1}^{N} \eta_j^S + \sum\limits_{j=N-i+2}^{N} \eta_j^S\right)}{\kappa} \\ \text{for } \ i \leq \frac{N}{2} \\ \tau . \dfrac{\eta_i^M + q\eta_{N-i+1}^M + \upsilon\left(\sum\limits_{j=i+1}^{N} \eta_j^S + q \sum\limits_{j=N-i+2}^{N} \eta_j^S\right)}{\kappa} \\ \text{for } \ i > \frac{N}{2} \end{cases} \tag{12}$$

where η_i^M and η_i^S denote average spectral efficiency in level i under MeNB and HeNB, respectively, τ ranges from $0 \leq \tau \leq 1$ and denotes the loading condition of the network; whereas $\tau = 0$ indicates a fully-idle network, $\tau = 1$ indicates a fully-loaded network and υ denotes the number of times a resource block is allocated to SUEs in a level.

IV. Simulation Results

The performances of the proposed scheme have been evaluated in terms of throughput, outage probability and ASE. The HeNBs are overlaid on macrocells with radius of 1km. In any particular level/zone macrocell and small cell users are allocated mutually exclusive channels. For simplicity only one SUE per HeNB is considered where each channel is allocated to only one SUE in one particular level. The simulation parameters are given in Table I.

Fig. 3 shows comparative spectral efficiency for both MUE and SUE and combined average spectral efficiency achieved by the proposed scheme for various values of N. Though there is large variation between MUE and SUE spectral efficiency for understandable reasons, improvement for ML-SFR compared to SFR looks limited at a first glance. For example, when considering the 10^{th} percentile, for increasing the value of N from conventional 2 to 4 and 8, SUE achieves a spectral efficiency improvement of only 0.5 bps/Hz and 1.5bps/Hz respectively. For MUE with the same setup, improvement is approximately 1.25 bps/Hz is achieved for N=4. Interestingly, when N=8, spectral efficiency is actually remains nearly same and at higher percentile values it even reduces slightly. We therefore need to have a deeper look and to do further analysis to unfold the benefit of ML-SFR scheme.

TABLE I. Simulation Parameters

Parameter	Value	
Network layout	2-tier (13 cells)	
Cell radius	1 km	
Small cell radius	30 m	
MBS transmit power	100 W	
SAP transmit power	20 mW	
Bandwidth	10 MHz	
No. of RB	50	
N_o	-174 dBm/Hz	
Sub-carrier spacing	15 kHz	
Pathloss model	Outdoor	$28 + 35log_{10}(d)$ dB
	Indoor	$38.5 + 20log_{10}(d) + 7dB, 0 < d \leq 10$ $38.5 + 20log_{10}(d) + 10dB, 10 < d \leq 20$ $38.5 + 20log_{10}(d) + 10dB, 10 < d \leq 20$
γ	SFR-2	-6 dB
	SFR-4	{-3, -10} dB
	SFR-8	{-3, -8, -12.8, -17} dB
α	0.7	

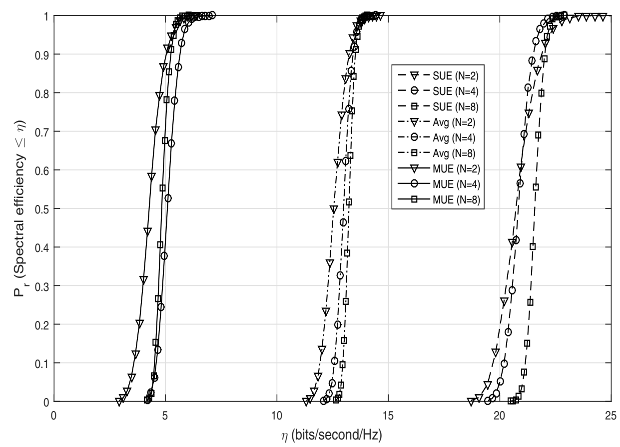

Fig. 3. Comparative spectral efficiency of the ML-SFR (N = 4, 8) and conventional SFR (N = 2) scheme

As discussed in the theoretical analysis part (Section II), ML-SFR makes much higher amount of spectrum available for small cells compared to SFR. So, even though the spectral efficiency improvement seems limited, due to higher spectrum availability, ML-SFR achieves massive capacity growth as evident form Figure 4. It can be seen that the proposed scheme with $N = 4$ almost doubles the the overall cell throughput compared to the conventional SFR ($N = 2$). Furthermore, if the number of levels are increased to 8, the throughput reaches to 1.2 Gbps which is more than three times higher compared to that of the conventional SFR and twice the throughput obtained for $N = 4$.

Apart from achieving massive capacity improvement in hetnet environment, the proposed scheme also reduces the

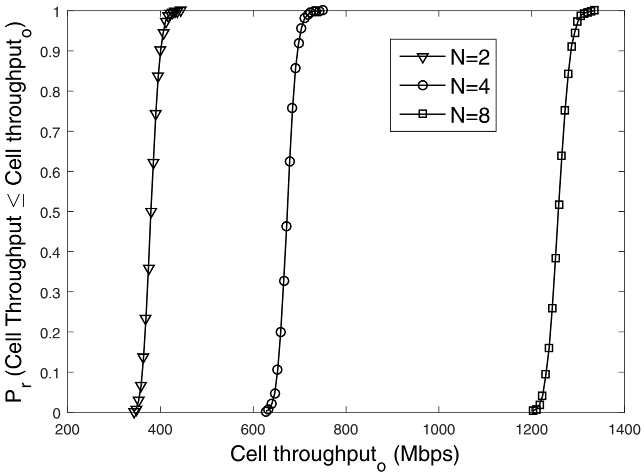

Fig. 4. Improvement of cell throughput due to the ML-SFR HetNet

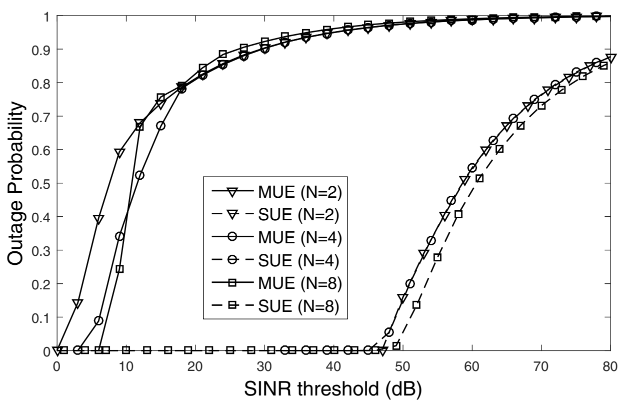

Fig. 5. Impact of the proposed scheme on the outage probability of the MUEs and SUEs

outage probability significantly. As is seen in Figure 5, the outage probability of SUE is far less than that of MUE; for a particular outage probability, SUE can satisfy about six times higher SINR threshold compared to MUE. The proposed scheme improves the outage probability of MUE more compared to that of SUE. For a SINR threshold of 8 dB, while the probability of the conventional SFR is 0.5, it goes down to 0.25 and 0.1 for $N = 4$ and $N = 8$, respectively, which is twice and five times lower than that of the conventional SFR. For SUEs, while the use of $N = 4$ cannot improve the outage probability, $N = 8$, however, attains the outage probability reduction of about 0.1 compared to the conventional one.

Another important performance indicator is Area Spectral Efficiency (ASE) which is particularly useful in understanding the performance in the hetnet environment where deployment is unplanned and density of deployment is much higher. Figure 6 compares the performance of ML-SFR with SFR in terms of ASE. It reveals that the proposed scheme with $N = 4$ far outperforms the conventional SFR. The ASE of the HetNet with $N = 4$ is more than twice the ASE of the conventional SFR HetNet. At CDF level of 0.1, while the ASE of the conventional SFR HetNet is 17 bps/Hz/cell, it is 43 bps/Hz/cell

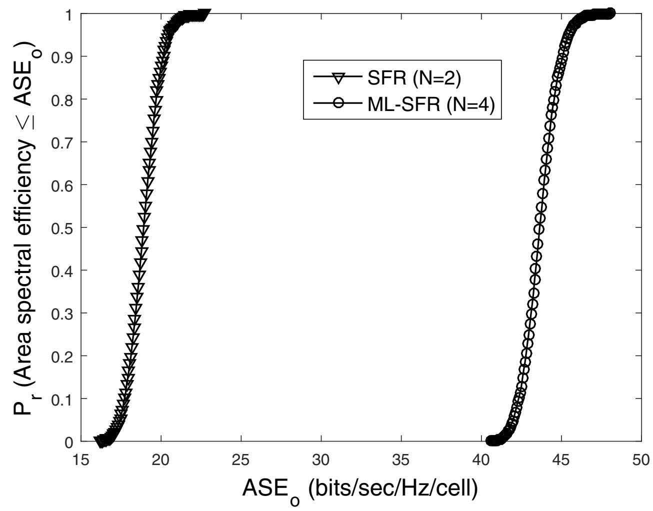

Fig. 6. ASE improvement compared to the conventional scheme

for the proposed scheme. Similar improvement can be achieved with higher value of N, though practical implementation will be complicated as the geographical separation between layers decreases with increased value of N.

V. Conclusion and Future Work

In this paper, we have proposed a cell deployment and resource distribution framework by applying multiple SFRs in a cell. Generalized expressions for spectrum and power allocation were presented both for macrocell only system and for HetNet environment. In addition, the cell throughput of the proposed ML-SFR scheme in the HetNet scenario has also been derived. Through simulations, we demonstrated that significant increase in cell throughput and ASE could be achieved by the proposed scheme. In addition, it significantly lowers the outage probability compared to the conventional SFR. If the density of HeNB deployment is increased, the performance will further improve in terms of ASE and network throughput while mostly following the similar performance pattern as presented in this paper subject to efficient intra-tier interference management which is a potential route for future exploration.

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